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Ship Materials Engineering Department

Research and Development Report

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Acoustic Behavior of Negative Poisson's Ratio Materials

by

Barbara Howell, Ph. D.

Mr. Pat Prendergast

Mr. Larry Hansen

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ABSTRACT

Negative Poisson's ratio (NPR) materials have been predicted to have unusual acoustic properties. To measure this effect, polyurethane foam was chosen to serve as a model system. Negative Poisson's ratio materials were produced from open cell, reticulated polyurethane foams by heat setting the foam which was compressed in three dimensions to a volume smaller by the factor 3.7 than the original volume. Acoustic tests comparing the reflection properties of the unconverted, the NPR uncovered, and the NPR foam with an attached cover, and one with an unattached covering were made on foams with pore sizes ranging from 10 to 100 pores per linear inch. Uncovered NPR foams reflected less sound at all frequencies than the uncovered unconverted foam. Smaller pore size NPR foams absorbed sound more efficiently at frequencies above 630 than did those with larger pores, and those with covers were better sound absorbers in the frequency range 250 to 1000 Hz than the uncovered NPR foams. Unidirectional compression to 1/4th the original thickness reduced the Poisson's ratio to zero and caused the foam to absorb nearly as well as did creation of the negative Poisson's ratio.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The purpose of this investigation is to determine whether porous foams which have been treated so that they have negative Poisson's ratios (NPRs) have superior acoustic absorbing properties to those of comparable foams which do not have negative NPRs.

During the 20th century, control of noise in industrial and military settings has become increasingly important. In response, attempts to develop a theory of sound absorption in porous materials were made by many investigators. Rayleigh [1929]was among the earliest to formulate a theory, and he recognized that a sound wave falling on an absorber continues to be propagated as a wave in air in the porous material. His work was extended by other theoreticians, among them, R. A. Scott.

Scott [1945] has worked out a theory for acoustic wave propagation in homogeneous, isotropic porous media which have pores with irregular shapes. According to this theory sound transmission involves motion of the foam fibers acted upon by the moving air, as well as motion of air in the irregular pore spaces. Air motion is influenced by "the pressure of the initial sound wave, the movement of fibers, and the inertial, compressive and viscous forces associated with the confined air". The theory developed provides an excellent fit to the experimental data at frequencies of 400 Hz and above. To test the theory, impedance measurements were made on Stillite rock wool backed with a rigid material. Reported investigations show that for frequencies of 100 Hz, the velocity of sound in the porous material is about one-third of that for free air, whereas at frequencies above 4000 Hz the sound velocity approaches that in free air. Scott's results indicate

further that at low frequencies the compression of air in the sound wave is isothermal, but at high frequencies it becomes adiabatic.

As acoustic science has developed, a variety of materials have been used as acoustic absorbers which include such materials as rockwool, glass fiber insulation, perforated acoustic tiles and plastic foam. Advantages of plastic foam, as described by Joseph Pizzirusso [1981] of Scott Paper Co., include the fact that the foam can be molded to a desired shape, and that it does not shed or allow fibers to escape into the environment. In addition foams can be tuned to absorb sound at a desired frequency by adjusting pore size.

Pizzirusso also discusses factors which contribute to making foam an effective sound absorber. To be effective, the foam must allow a sound wave to penetrate. Foams with a reticulated cell structure, that is open cells from which the cell walls have been removed so that only the ribs remain, allow sound penetration better than foams with closed or partially open cells, and are therefore more efficient sound absorbers. Reticulated foams are prepared by removing cell walls by thermal or chemical processing. Vibration of the cell ribs converts acoustical energy into heat and produces sound absorption. The superiority of reticulated foam is more evident at high, rather than low frequencies.

Pizzirusso discusses other physical properties which affect acoustic absorption efficiency as well. These properties include thickness, pore structure, pore size, permeability, and surface treatment. Foam permeability is the most important property controlling efficiency, and usually increases with increasing pore size. However, pore surface roughness also affects permeability, as does the percentage of closed pores.

Since thermal wall removal leaves smoother ribs than when walls are removed by immersion in a caustic bath (chemical processing), thermally produced reticulated foams are more permeable than those produced by chemical processing other things being equal.

Smaller pore sizes absorb more efficiently than larger pores, up to approximately 4000 Hz according to Pizzirusso. Above 4000 Hz the sound wave may bounce off the surface, so it is important to have as many open cells as possible to allow the sound wave to penetrate into the foam. Increasing foam thickness is often useful, especially at lower frequencies. Ideally the foam thickness should be one quarter of the sound wavelength.

When blockage of sound transmission through a sound barrier is the principal concern, use of a solid backing for the foam is advantageous, since the backing will reflect sound not absorbed by the barrier. A thin layer of aluminum or cardboard is adequate for this purpose. Use of a backing material to reflect sound causes the reduction of transmitted sound to be more than double that of an equal thickness of unbacked foam. It is believed that the reflected sound may be out of phase with that coming in, resulting in destructive interference of the sound wave. Small openings through the foam greatly reduce its sound absorption effectiveness.

Methods for tuning the acoustic foam to absorb sound at a desired frequency have also been described by Pizzirusso [1981]. Reticulated foams can be produced to absorb in the low and medium frequencies. This is done by means of a hot-rolled pressing process which puts a skin on the front face. Selected frequency absorption can also be obtained by compressing the foam to produce a felt (tile). The extent of compression controls the

frequency at which the foam will absorb, with higher frequency absorption produced by more compressed foam.

Robert Lambert [1982] of the University of Minnesota has developed theory for sound propagation in highly porous open-cell elastic foams. He indicates that for a wide range of frequencies and wide ranges of mean pore size, the parameters required to describe the behavior are: dynamic flow resistance, inverse thermal time constant, volume porosity, dynamic structure factor and the ratio of sound velocity in the pores and in the solid. His theoretical results for highly porous, open cell, flexible foams are valid in the frequency range 16–6000 Hz and for pore sizes of 0.009 to 0.079 cm. Negligible coupling between sound waves in the pores and elastic waves in the frame of bulk materials is predicted by the theory for frequencies above 16 Hz.

For many applications it is necessary that an acoustic foam be coated with a film. If water or oil are likely to enter the foam, a film barrier is essential to preserve the acoustic qualities of the foam.

Two sets of investigators have described the effect of a surface film on the acoustic absorption of foamed materials. Schwartz and Buehner [1963] found that coatings of 0.005 g/cm^2 produced an increase in the low frequency absorbance of foams 1/2 to 1–inch thick, but addition of a thicker film (0.05 to 0.50 g/cm^2) caused a decrease in absorption except at a frequency of 240 Hz. They therefore investigated the influence of film thickness in relation to absorption efficiency at various frequencies. For foams with pore sizes of 50 to 70 per inch and a porosity of 97%, use of the thicker polyethylene film produced an absorption maximum at frequencies lower than 1000 Hz.

The second investigator, Andersson [1981] reports that use of films on acoustic materials can produce a design problem since application of film to a foam can degrade acoustic properties. Calculations made in this reference are used to predict that the film surface density should be less than 0.0085 kg/m^2, if acoustic properties of the foam are to be retained. For many polymer films this is a thickness of approximately 5 to 80 micrometers. Materials recommended for engine room use must be able to resist water, oil, and fatty acids in combination with steam cleaning, diesel oil, gasoline, and degreasing agents, and the film should swell no more than 5%. The film material should also be tough enough to withstand mechanical damage. Materials recommended for acoustic film are polyurethane, polyvinyl chloride, polyester and aluminum.

Different techniques have been used to apply these films. These are flame-lamination, gluing over the entire surface, point gluing, and simply wrapping the film material around the acoustic foam surface. It is important that there be no tension on the film when it is laminated to the foam surface. Of these procedures, flame lamination has been found most effective.

Negative Poisson's ratio (NPR) materials exist in nature but they are very uncommon. Single crystal pyrite, presumed to be from a twinned crystal, was found to have a Poisson's ratio of –0.14, and anisotropic single crystal cadmium may also have a negative value for this property. Certain honeycomb structures exhibit a negative value for this property [Lakes, 1987a] as well.

In 1987, Dr. Roderick Lakes [Lakes, 1987] discovered a method for producing materials in the laboratory which have negative Poisson's ratios. Potential uses [Chertas, 1990] for materials with this unusual property were quickly visualized, e.g., as a filler for

GORE–TEX Parkas, which keeps out liquid water but lets water vapor through. This NPR Teflon filler has formed the basis for an entire industry. Its unusual behavior results from its structure which consists of flat discs connected by thin filaments. When these fibers are stretched, the parallel arrangement of discs is disrupted, and the discs stand on edge as shown in Fig. 1. Other NPR materials may prove useful as construction materials, as acoustic absorbers, better artificial bones, shock absorbers (such as for wrestling mats), for gaskets and seals and for other purposes.

Dr. Lakes predicts that for NPR materials there are stop band frequency domains, and that there is very high material damping. The stop bands are produced by microresonance of the cell ribs which occur at lower frequencies for the bent ribs of the NPR materials than for the straight ribs of unconverted foams. The enhanced damping is also expected at lower frequencies for NPR materials because of viscoelastic effects and other effects associated with the re-entrant (NPR) structure. In these materials absorption and dispersive loss are attributed by Dr. Lakes to (1) viscoelastic loss, (2) structural effects modelled by Cosserat elasticity, and (3) structural effects from micro-vibration of the structural elements. The viscoelastic loss and Cosserat elastic effects are caused by an increase in wave speed with frequency and these combine to produce a dispersion curve which is concave up. Microvibrations, however, can cause the opposite dispersion and also cause cut-off effects. These are seen in closed cell foams, at MHz frequencies in composite materials, and at 10^{14} Hz in atomic lattices. Small values of Poisson's ratio correspond to dynamically floppy cells which have low cut-off frequency, stiffness and density. Lakes predicts that the cells of re-entrant foam materials will be dynamically floppy.

Dr. Lakes predicts further that stopbands can be identified from the dynamical mechanical behavior of a material, which gives a value for $\tan\delta$, the loss tangent (which is the complement of the phase angle d), as well as dispersion curves. In addition to a cut-off frequency, micro-vibration of the re-entrant foam ribs is predicted by Dr. Lakes to result in very low transmissibility of acoustic waves. To develop a theory of these materials he employs two approaches, a discrete modelling of the cell ribs, and a generalized continuum approach involving elasticity theory and microstructure. The result of this analysis is a prediction of the type of absorption dispersion, and of stopband behavior which are dependent on the structural characteristics of the re-entrant foam materials with negative Poisson's ratios. It is also predicted that for materials with a Poisson's ratio of –1, the material will become highly compressible and its bulk modulus will be much less than its shear modulus [Lakes, 1987].

Friis, Lakes and Park [Friis, 1988] also deal with the theory of NPR materials. For these, properties are determined by the type of cell (open, closed, or with some open and some closed cells), the volume fraction of the solid, and the cell structure. They state that cells of most man-made foams have a shape which can be modelled by the Kelvin minimum area tetrakaidecahedron. This geometric figure has square and hexagonal faces as shown in Fig. 2. When the foam is converted to a re-entrant material, the ribs are bent and the structure is shown in Fig. 3. For open cell foams the modulus of elasticity, E, is related to the foam density by the relation

$$\frac{E_{foam}}{E_{solid}} = \left[\frac{\text{foam}}{\text{solid}}\right]^2$$

which is useful for predicting mechanical properties. This equation applies also to closed cell foams where most of the density is in the ribs. However, Poisson's ratio for the foam to which this theory applies is 0.33 at all densities so it does not apply to NPR foams.

For a thermoplastic, a negative value for Poisson's ratio is produced by triaxial compression by a factor of 1.4 to 4 times. This compression is followed by heating the thermoplastic to its softening point, and cooling under the volume constraint.

Foams produced by Dr. Lakes and coworkers, were found to be more resilient than the parent material. Whereas the parent materials showed linear behavior only to a compressive strain of 5%, the re-entrant foams showed linear behavior to 40%. NPR foams prepared by Dr. Lakes, et al, include polyurethane, silastic and copper metal, prepared from the metal foam. Youngs modulus was measured for these materials from the slope of stress-strain curves, and found to be smaller for the re-entrant materials.

Unusual sound reflection patterns were predicted for NPR materials by Lipsett and Beltzer [Lipsett, 1988] as shown in Figs. 4, 5, 6 and 7 which are reproduced from their publication. As may be seen from these figures, the transverse wave, which forms as a longitudinal wave strikes an NPR surface, has markedly different properties from a similar wave formed by reflection from a typical acoustic foam. In addition, reflection properties are highly dependent upon the incident angle as well as the Poisson ratio. Wave velocity ratios are also predicted to vary markedly with changes in Poisson's ratio.

Because NPR foams have these unusual characteristics, it was considered worthwhile to test a model foam system for suitability to Naval applications. The polyurethane acoustic foam chosen to serve as a model system has open cells and is reticulated. For the first set of acoustic measurements, NPR foams were made by Dr. Lebovits and acoustic measurements were made by Noise Unlimited. For the second set, NPR foams were made by Dr. Howell and acoustic measurements were made by Larry Hansen of the Applications and Special Projects Branch of DTRC. Several pore sizes were investigated for both sets of measurements.

EXPERIMENTAL MATERIAL

Polyurethane foams were obtained from Airtex Industries, Industrial Gasket Co., Illbruck/USA, Belting Industries Co. and from Scotfoam Co. Those obtained from Scotfoam were selected for the preparation of NPR materials and were used for the acoustic measurements because they are reticulated foams.

Acoustic measurements were made for foams with 10, 30, 45, 80 and 100 pores per linear inch. Tests were run on the unconverted material and on the material converted so as to give a negative Poisson's ratio, with and without a covering layer of polyethylene. Some tests were run with 4 mil polyethylene and some with 2 mil polyethylene attached by heat treatment to the foam. Comparisons were also made to a 90 pore per linear inch foam which had been compressed to 1/4th its original thickness.

Negative Poisson's ratio films were produced by compressing octagonal shaped pieces of foam, 6 in. in diameter and 2 in. thick in a cylindrical mold 1 5/8 in. deep and 4

7/8 in. in diameter. Mold and foam were heated to 260°F for 35 min, as measured by a thermocouple embedded in the foam, the oven was shut off and the assembly was allowed to cool. A second compression step was performed similarly in a cylindrical mold 1 1/4 in. deep and 4 1/16 in. in diameter, which produced an overall compression of 3.7 times.

Cylindrical samples 1 1/8 in. in diameter by 1 1/4 in. tall were used for the higher frequency set of acoustic measurements.

Permeability measurements were made by applying a pressure of 2.5 lb per square inch and measuring the height of a mercury column supported as air passed through the film. Light microscope photographs were taken of the unconverted foam and of the NPR foam at a magnification of 20x.

The percentage of air in a foam sample was estimated by weighing the foam, measuring its volume, and making use of the density of polyurethane.

ACOUSTIC MEASUREMENT

A standing wave apparatus (B&K Type 4002) was used to measure the acoustic absorption coefficient and the acoustic impedance of samples of the foam materials [Bruel & Kjaer]. This apparatus consists of a metal tube attached to a loudspeaker at one end and having a removable cap at the other in which a sample of the material to be tested is placed. The pressure variations in the tube are measured by means of a travelling probe consisting of a microphone attached to a long thin tube. The probe is inserted through a hole in the center of the speaker magnet, so its end can be put anywhere along the axis of the standing wave tube. The arrangement is shown in Fig. 8.

The sound from the speaker enters the tube and travels toward the sample, which is a disk cut to fill the whole end cap. The tube is sized so that by the time the wave reaches the sample, it will have become a plane wave. The sample absorbs part of the energy in the wave and reflects part. The presence of both the incident and reflected waves in the tube at the same time gives rise to a "standing wave" which is a stationary pattern of acoustic pressure amplitude. The resulting amplitude is maximum at places where the wavefronts are in phase, and minimum where they are out of phase. The ratio of maximum to minimum amplitude is called the standing wave ratio (SWR) and depends on the portion of the incident pressure which is reflected. If the sample is perfectly reflecting, the maxima will be twice the incident amplitude and the minima will be zero. If the sample is perfectly absorbing, there will be no maxima or minima, only the amplitude of the incident wave. The axial distance between maxima, or between minima, is one-half wavelength and is determined by the frequency of the sound and its velocity.

The tip of the microphone probe can be moved along the tube until the first maximum is located. The amplitude at this point is measured and recorded. The probe is then moved to the first minimum where the amplitude is also measured and recorded. The ratio between these two values can be used to calculate the absorption coefficient. The apparatus is equipped with a scale which is used to measure the location of the minima. These are needed to calculate the phase angle between the waves. The phase angle is in turn needed to find the acoustic impedance of the sample. The required calculations are shown in Appendix A. In general, the coefficient and the impedance are functions of frequencies over the range of interest. The established octave band or one-third octave band

the range of interest. The established octave band or one-third octave band center frequencies are usually used for these measurements to be consistent with the literature.

ABSORPTION MEASUREMENTS

Each sample was placed in the apparatus and measurements made at various one–third octave band center frequencies in the frequency range from 100 Hz to 6300 Hz. At each frequency, the first maximum was located and the sound level set to a known value. The first minimum was then located and the corresponding sound level was measured and recorded. The absorption coefficient was calculated for each data point using the method given in Appendix A.

The first test condition was the baseline. Measurements were made with no sample in the tube. Only the metal sample holder was in place over the end of the tube during these measurements. Curves in the plotted results showing this condition are labeled "Base" or "Baseline". These are included on all the plots.

The second test condition was with the bare foam surface of the sample facing the sound source. Curves showing this condition are labeled "Open".

The third test condition was with a film placed over the surface facing the sound source and held with Scotch tape. Curves showing this condition are labeled "Closed".

The fourth test condition was with a film fused to the surface facing the sound source. Heat was used to bond the film to the sample. Curves showing this condition are labeled "Fused".

The fifth test condition was with a foam which was processed differently than the others in that it was compressed in only one direction while being cured. Curves showing this condition are labeled "Tile".

Measurements between 100 Hz and 1600 Hz were made using a 100 mm diameter tube, and those between 2000 Hz and 6300 Hz were made using a 30 mm diameter tube. The time available did not allow testing of every material over the full frequency range so some were only done in the lower frequency tube which was considered the most important range.

IMPEDANCE MEASUREMENTS

In addition to the maximum and minimum amplitudes, the distances from the sample surface to the first maximum and first minimum were recorded as well. These are needed to calculate the acoustic impedance using the method given in Appendix A. These calculations were deferred because of time limitations.

RESULTS AND DISCUSSION

Permeability measurements made on the unconverted and converted reticulated polyurethane foams which have several different pore sizes are shown in Table 1 as are the Poisson's ratios and the percent of polyurethane (The remainder is air.). Photographs of the two types of foam and a comparable foam (a tile) which has been compressed to 1/4 its original thickness, are shown in Fig. 9. Comparison of the unconverted foam (Fig. 9a) with the tile show that openings are flatter, and in general they appear to be smaller

than in the unpressed foam. The NPR foam merely appears to have smaller pores, and the ribs are sometimes bent.

Table 1. Polyurethane foam properties.

Sample	Pores per linear inch	Percent Polyurethane Unconv	Relative Permeability	Poisson's Ratio
SIF 30	30	3.1	14	0.23
SIF 30 conv			12.9	–0.14
SIF 80	80	3.7	5.9	0.33
SIF 80 conv			4.8	–0.11
SIF 90 tile				0.00

From this table it can be seen that compressing the material to produce a NPR decreases the permeability by approximately 9 percent. It should also be mentioned that when the NPR materials were stretched by more than about 10 percent, they began to exhibit a positive Poisson's ratio. The percent of polyurethane (the remainder is air) was calculated from foam density and density of polyurethane which was taken to be 1.05 g/mL.

Calculated values of the absorption coefficient were plotted against one-third octave frequencies to compare foams of different pore densities with and without film coverings. Plots were also made to compare processed (converted to NPR) and unprocessed foam samples. The plots are described below.

It was found that a peak appeared in all the data, including the baseline data, at 315 Hz. This peak was considered to be an artifact caused by a tube resonance. We were unable to avoid this effect by damping the tube, changing the excitation amplitude or filtering. The problem was cured by replacing the data for 315 Hz in all the curves, with the average of the values for the adjacent points (250 and 400 Hz).

The first plot (Fig. 10) compares different conditions of 30 pore per linear inch (SIF–30) foam along with the baseline. This plot shows the difference between the unprocessed and the processed (NPR) foam and the effect of placing a protective film on the surface. It can be seen that there is a definite improvement in absorption in the frequency range above 200 Hz for the processed "open" foam compared to the unprocessed. The film covered conditions appear to work even better between 200 and 1000 Hz. They may not be as good an absorber above 1000 Hz but more data is needed to confirm this. The curve for the "fused" condition seems to tend downward, but has peaks at two of the higher frequencies.

The second plot (Fig. 11) compares different conditions of 80 pores per linear inch (SIF–80) foam with the baseline. The results are similar to that found with SIF–30 foam in that the processed (NPR) foam shows a similar improvement in the 200 to 1600 Hz range. At frequencies below 200 Hz, all the curves converge and tend toward poor absorption. At high frequencies, the "open" foam and the "tile" both had good absorption.

The third plot (Fig. 12) compares foams of various pore densities with their bare surface facing the sound source ("Open"). The baseline is also shown. It can be seen that the absorption generally increases with increasing pore density. The curve for the SIF–90

(90 pores per linear inch) tile compares favorably with the SIF–80 NPR foam at frequencies below 1000 Hz and exceeds it at the higher frequencies, but absorption of the NPR SIF–100 (100 pores per linear inch) foam is better at frequencies above 1000 Hz than that of the SIF–90 tile. Comparable absorption of the tile with the NPR foams is a good sign because this process seems to be more amenable to production of continuous or large sheets of the material.

The fourth plot (Fig. 13) compares foams of various pore densities with a 4 mil polyethylene film taped over the surface facing the sound source ("Closed") or with the polyethylene film heat bonded to the surface facing the sound source ("Fused"). The absorption of the covered foams tended downward in the high frequency range with the "fused" condition being particularly poor. It is believed that this behavior is due to the looser film being able to move and pump air into the pores while the fused film is more rigid and reflects the sound.

Measurements described in this report were made at normal incidence so that the predictions made by Lipsett and Beltzer [1988] for sound wave reflections at smaller reflection angles cannot be verified from the experimental data obtained. Additional experiments made with different incident angles would therefore be informative.

CONCLUSIONS

Foams with a negative Poisson's ratio were shown to be better acoustic absorbers over the entire frequency range 100 to 1600 Hz when compared with unconverted materials.

At frequencies below 200 Hz, all absorption curves converged and tended toward poor absorption, but the polyethylene covering on the foam improved absorption below 500 Hz. At frequencies above 630 Hz, uncovered NPR foams were superior and the foam with the smallest pore size showed the best absorption.

Compression of the foam in only one dimension decreases the Poisson's ratio and has nearly the same influence on acoustic properties as production of a negative Poisson's ratio.

Acoustic absorptions found for the different materials investigated provide guidelines for selecting materials to give absorption in a particular frequency range.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the work done by Dr. Alex Lebovits who performed the literature search for this project and established the techniques for producing negative Poisson's ratio materials from polyurethane foam.

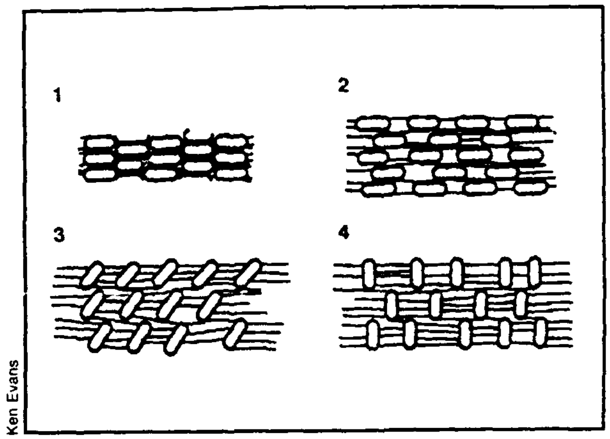
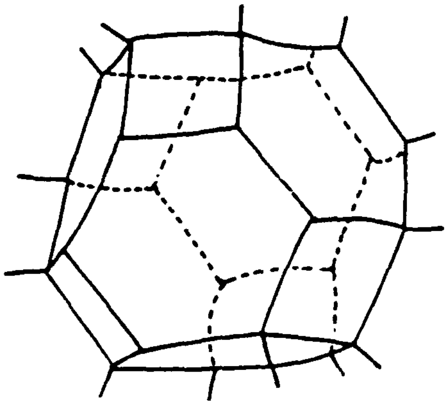


Fig. 1a. A micrograph of PTFE showing the discs and connecting strands which comprise the negative Poisson ratio (NPR) material.

Fig. 1b. When stretched, the NPR PTFE expands because the strands tilt the discs so that the material bulk is increased.

Fig. 1. A micrograph of PTFE. (© Used with permission of Dr. Ken Evans and Jeremy Cherfas. Taken from "Stretching the Point", *Science*, Vol. 247, 9 Feb 1990, p. 630. Copyright 1990 by the AAAS.)



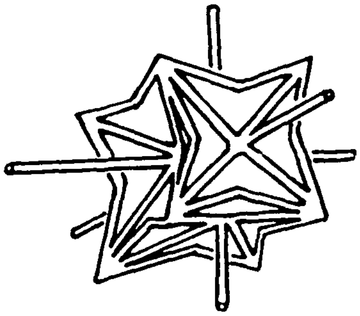


Fig. 2. The tetrakaidecahedron which describes the cellular structure of the unconverted polyurethane foam. (© Used with permission of Dr. R. Lakes. Taken from "Foam Structures with a Negative Poisson's Ratio", *Science*, Vol. 235, 27 Feb 1987, p. 1038. Copyright 1987 by the AAAS.)

Fig.3. The tetrakaidecahedron after the polyurethane foam has been converted to an NPR material. (© Used with permission of Dr. R. Lakes. Taken from "Foam Structures with a Negative Poisson's Ratio", *Science*, Vol. 235, 27 Feb 1987, p.1038. Copyright 1987 by the AAAS.)

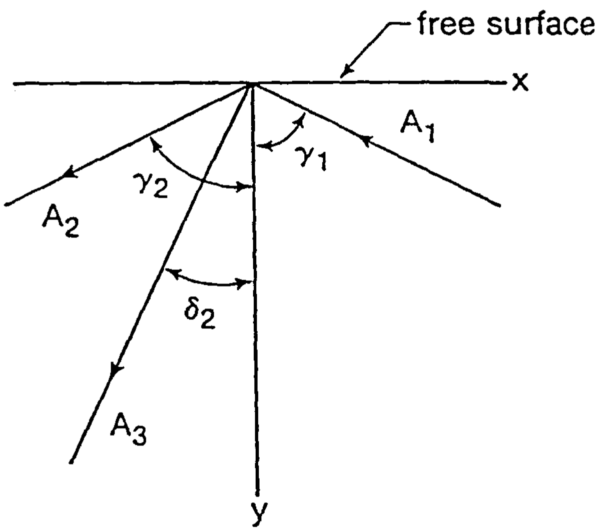


Fig. 4. A sound wave is incident at angle γ_1 with amplitude A_1, and is reflected with a longitudinal component at angle γ_2 of amplitude A_2 and transverse component at angle γ_3 with amplitude A_3. (© Used with permission of W. A. Lipsett. Taken from *J. Acoust Soc. Am.*, Vol. 84, No. 6, 1988.)

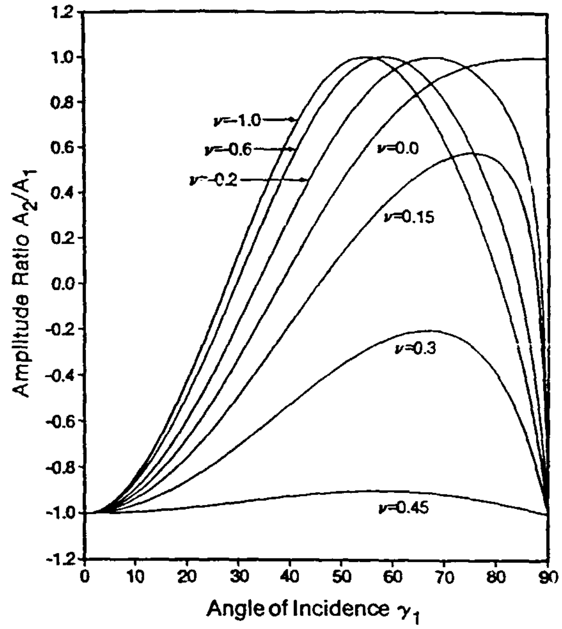


Fig. 5. The predicted incident and reflected longitudinal amplitude ratios are plotted as a function of angle of incidence for different values of the Poisson ratio. (© Used with permission of W. A. Lipsett. Taken from *J. Acoust Soc. Am.*, Vol. 84, No. 6, 1988.)

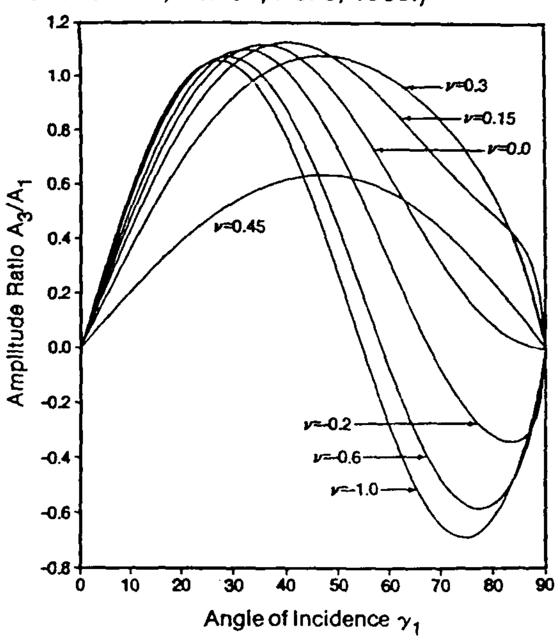


Fig. 6. The ratio of predicted reflected transverse amplitude to incident longitudinal amplitide at different incident angles for different values of the Poisson ratio.(© Used with permission of W. A. Lipsett. Taken from *J. Acoust Soc. Am.*, Vol. 84, No. 6, 1988.)

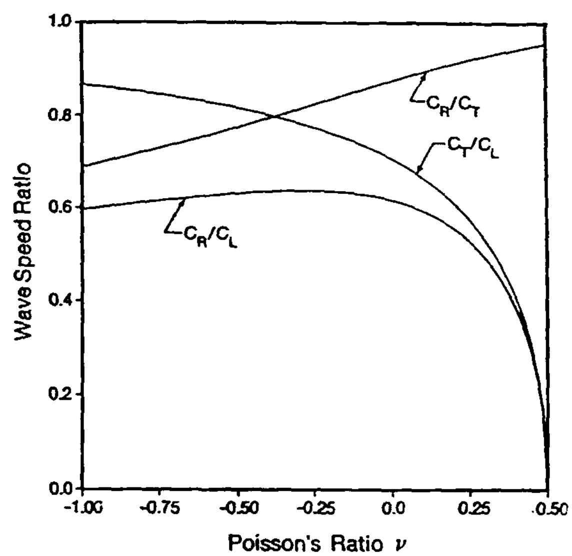


Fig. 7. Wave speed ratios are compared for C_R/C_T, C_R/C_L, and C_T/C_L for different values of the Poisson ratio. C_R is the Rayleigh wave speed, C_T is the transverse wave speed and C_L is the longitudinal wave speed. (© Used with permission of W. A. Lipsett. Taken from *J. Acoust Soc. Am.*, Vol. 84, No. 6, 1988.)

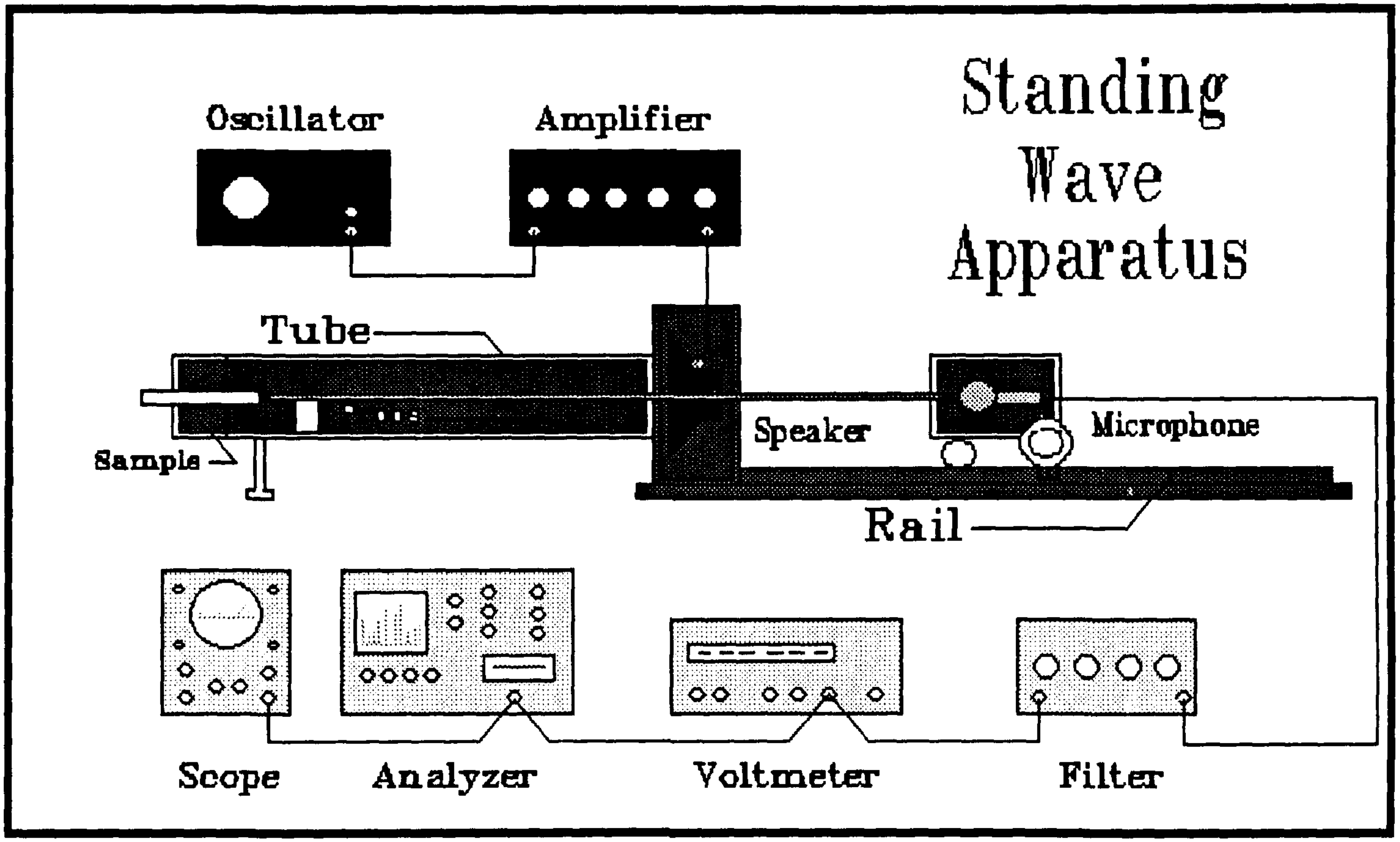
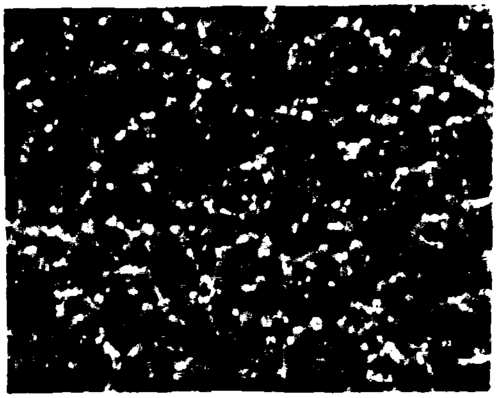
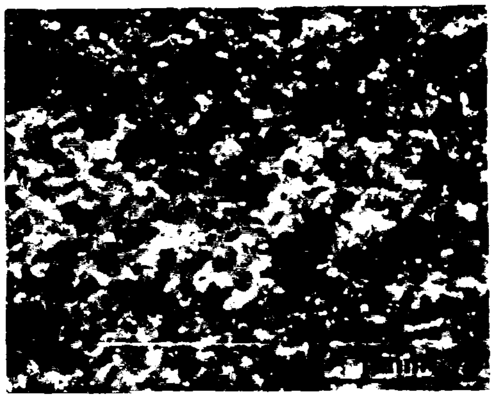


Fig. 8. Schematic of the B & K impedance tube.



(a)



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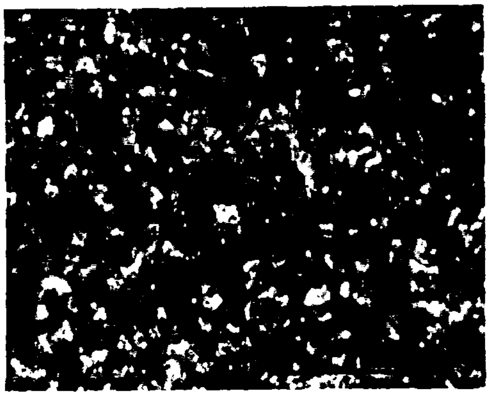

(c)

Fig. 9. Comparison of the microstructure of (a) the unconverted 100 ppi foam, (b) the negative Poisson ratio foam, and (c) the 90 ppi tile.

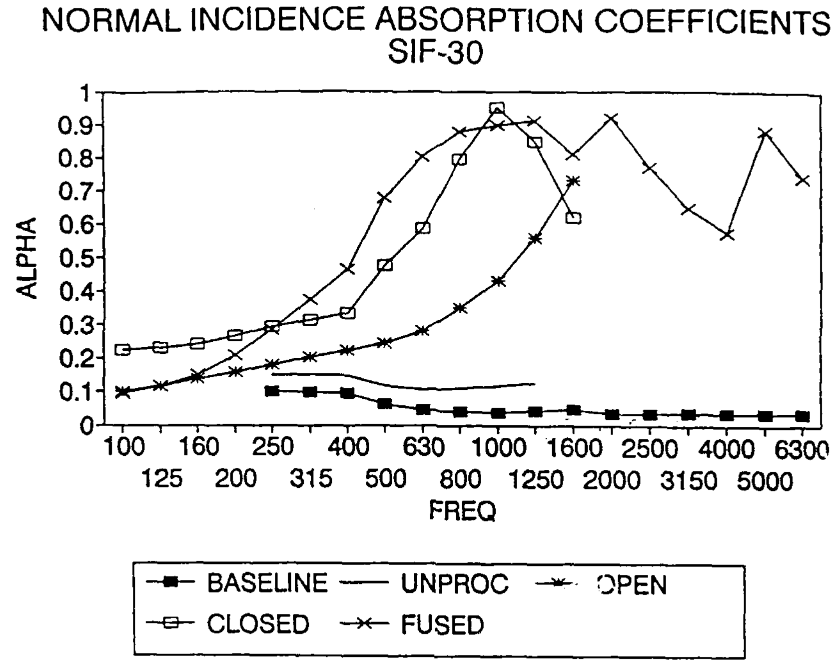

Fig.10. Absorption coefficients (α) for SIF–30 polyurethane foam for unconverted, and negative Poisson ratio foam without a cover (open), with an unattached cover of polyethylene film (closed), and with an attached film (fused).

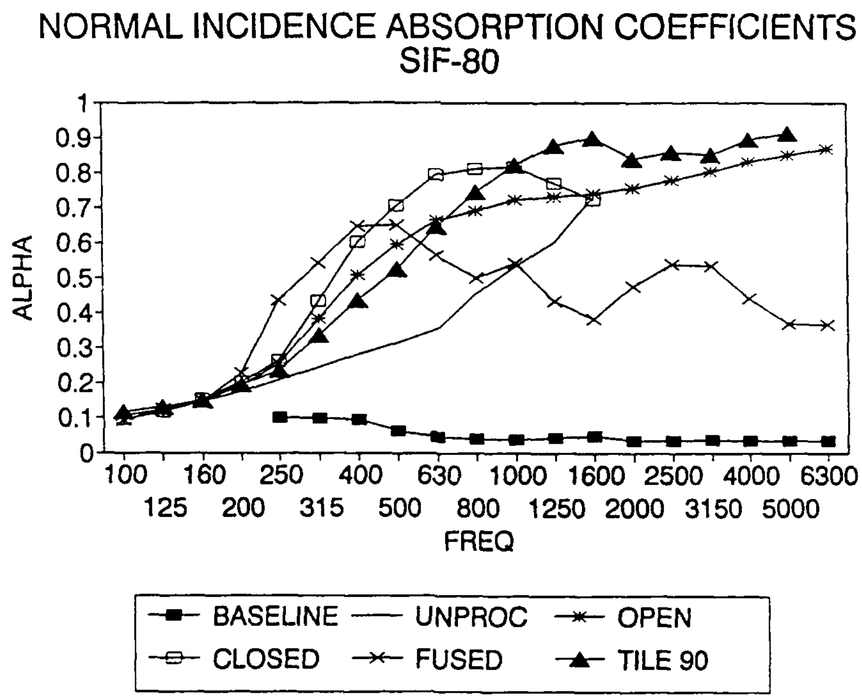

Fig. 11. Absorption coefficients (α) for SIF–80 polyurethane foam as in Fig. 2, with SIF–90 tile in addition.

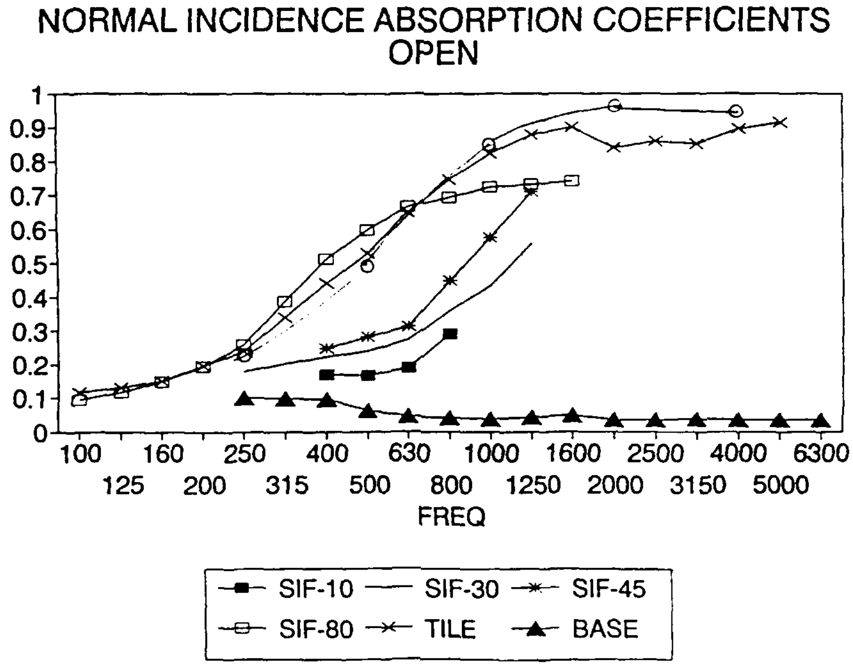

Fig. 12. Absorption coefficients (α) for uncovered NPR foams of different pore sizes and for the SIF–90 tile. (Measurements on the 100 ppi foam were made by Noise Unlimited).

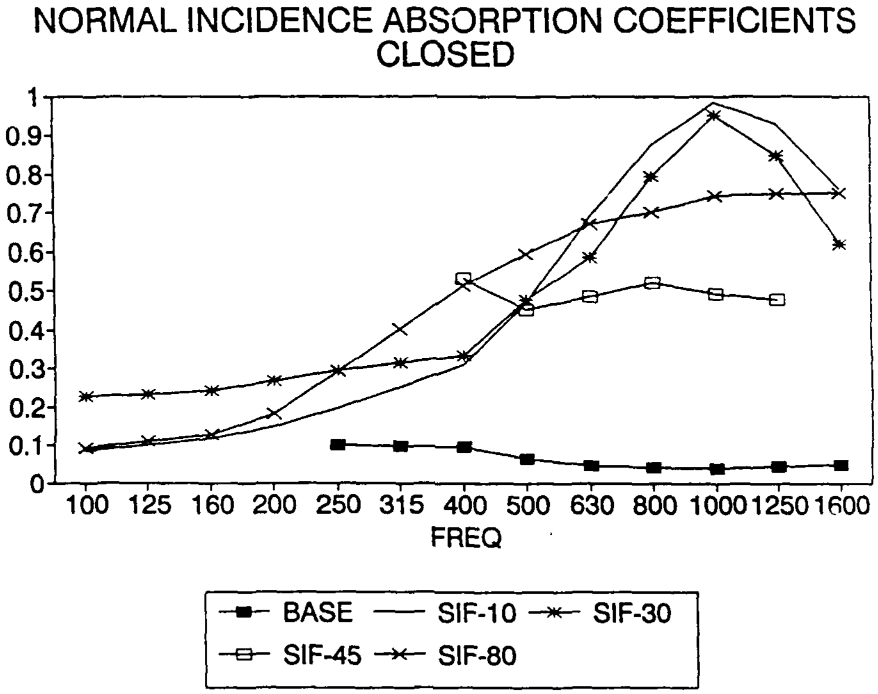

Fig. 13. Absorption coefficients (α) for covered (NPR) foams of different pore size.

APPENDIX A

STANDING WAVE APPARATUS CALCULATIONS ABSORPTION COEFFICIENT

(The calculations given below were adapted from the Bruel and Kjaer Instruction Manual for the Standing Wave Apparatus, [Bruel and Kjaer and Reynolds, 1981]).

p_i = Incident sound pressure (Pa)

p_r = Reflected sound pressure (Pa)

f = Frequency (Hz)

y = Distance from sample surface to microphone probe (m)

c = Velocity of sound (m/s)

t = Time (s)

$\omega = 2\pi f$

I = Amplitude of incident wave

R = Amplitude of reflected wave

r = Ratio between reflected and incident amplitudes

n = Ratio between amplitude minima and maxima

d = Phase angle between incident and reflected waves.

The incident wave pressure in the tube is sinusoidal and is given by:

$$p_i = I\cos(\omega t)$$

The reflected wave, having made a round trip to the surface and back, is given by:

$$p_r = R\cos(\omega(t-2y/c)+d)$$

At any point in the tube, the pressure will be the sum of the incident and reflected wave pressures.

$$p_y = I\cos(\omega t) + R\cos(\omega(t-2y/c)+d)$$

$$p_y = I\cos(\omega t) + R\cos(\omega t)\cos((2\omega y/c)+d) + R\sin(\omega t)\sin((2\omega y/c)+d)$$

If we let d = 0 for now (the perfect reflector case);

$$p_y = (I+R)\cos(\omega t) \text{ when } y = L/2$$

such that $\cos(2\omega y/c) = 1$ and $\sin(2\omega y/c) = 0$

$$p_y = (I-R)\cos(\omega t) \text{ when } y = L/4$$

such that $\cos(2\omega y/c) = -1$ and $\sin(2\omega y/c) = 0$

The above is an interference of two coherent waves so the result could have been expected;

Maxima occur at multiples of y = L/2 with amplitude I+R

Minima occur at multiples of y = L/4 with amplitude I–R

The ratio of max/min; $n = (I+R)/(I-R)$

This can be rewritten as: $r = R/I = (n-1)/(n+1)$

The absorption coefficient

Alpha (α) = energy absorbed/incident energy

The energy is proportional to the square of the pressures;

The energy absorbed is equal to the incident minus the reflected energies $= I^2 - R^2$

so $\alpha = (I^2 - R^2)/I^2 = 1-(R/I)^2$

which can be expressed as;

$\alpha = 1 - \{(n-1)/(n+1)\}^2$

In order to operate without distortion, the speaker level at the maximum was set to a certain level and then the minimum was measured in dB relative to this level. The difference in dB between the dB(max) and dB(min) was converted to a voltage ratio by:

$n = 10\exp(dB/20)$

Then n–1 and n+1 were calculated and subsituted into the formula for Alpha given above.

ACOUSTIC IMPEDANCE

The acoustic impedance is the ratio between the pressure and the particle velocity normal to the surface. This is in general a complex quantity because the velocity may not necessarily be in phase with the pressure.

Consider the incident wave in Fig. A–1 travelling to the right with constant velocity c and amplitude I. The reflection of this wave by the surface will be a wave travelling to the left at the same velocity but with amplitude R and offset by phase angle d (which we ignored in the previous calculation). As mentioned above, the pressure in the tube will be a standing wave whose maximum amplitudes will be spaced one-half wavelength apart. This is because the relative velocity of the two waves travelling in opposite directions is twice that of each wave individually (2c).

If the sample in the tube is a perfect reflector then a maximum will occur at it's surface and the first minimum will be 1/4 wavelength (L/4) away. In the other extreme case, there would be no reflection and hence no minimum. Real materials however, only partially reflect, thus making the pressure at the surface less than the maximum. There can also be a difference of phase between the incident and reflected waves causing a shifting of the locations of the maxima and minima. A measurement of the distance from the surface of the sample to the first minimum will therefore determine the amount of the phase shift. Note that the minima are more sharply defined than the maxima, so they provide more accurate measurements.

L = Wavelength of sound in the tube.

y_1 = Distance from the surface to the 1st minimum.

y_2 = Distance from the surface to the 2nd minimum.

c = Velocity of sound.

r_o = Density of air

d = Phase angle between incident and reflected waves.

n = Ratio between amplitude minima and maxima.

r = Ratio between reflected and incident amplitudes.

v = Particle velocity

Z = Acoustic Impedance

$$L/2 = y_2 - y_1 \text{ in meters}$$

$$d/\pi = 1 - y_1/(y_2 - y_1)$$

$$d = y_1\pi/(y_2 - y_1)$$

$$d = y_1 2\pi/L$$

If the distance y_1 is greater than L/4 then the phase angle is positive. This corresponds to the situation where a maximum occurs before the first minimum.

If this distance is less than L/4 then the phase angle is negative. This corresponds to the situation where a minimum occurs first.

$$p_i = I\exp(j\omega t)$$

$$p_r = R\exp[j(\omega t - (2\omega y_1/c) + d)]$$

$$p_r = (R/I)p_i\exp[-j((4\pi y/L) - d)]$$

The expression is a minimum when

$$(4\pi y_1/L) - d = \pi$$

$$d = [(4y_1/L) - 1]\pi$$

or

$$d = [(2y_1/(y_2 - y_1)) - 1]\pi$$

The apparatus used restricts the sound to the normal-incidence plane-wave case, thus simplifying the interpretation of the data.

$$Z = Z(\text{normal}) = (p_i + p_r)/(v_i + v_r)$$

since, for a plane wave in air, $v = p/r_oc$

$$Z = [(p_i + p_r)/(p_i - p_r)]r_oc$$

$$Z = [(1 + (p_r/p_i))/(1 - (p_r/p_i))]r_oc$$

$$p_r = p_ir\exp(jd)$$

$$Z = [(1 + r\exp(jd))/(1 - r\exp(jd))]r_oc$$

This can be expressed;

$$Z = [\mathrm{Re}(Z) + j\mathrm{Im}(Z)]r_oc$$

Then;

$$\mathrm{Re}(Z) = (1 - r^2)/[1 + r^2 - 2r\cos(d)] \text{ and}$$

$$\mathrm{Im}(Z) = (2r\sin(d))/[1 + r^2 - 2r\cos(d)]$$

WAVELENGTH CALCULATIONS

Effect of Temperature Variation [Weast, 1970 and EB Div., General Dynamics, 1978].

$$c = c_o(1 + (T/273))\exp(1/2)$$

where c is in m/sec and T is in deg C

$c_o = 331.45$ m/s at 0 deg C

$c = 331.45 + .607T$

The temperature in the laboratory varied between approximately

70 deg F = 20 deg C $c = 331.45 + (.607)(20) = 332.66$

and

85 deg F = 23 deg C $c = 331.45 + (.607)(23) = 334.55$

$(334.55 - 332.66)/333 = .3\%$ variation in velocity which will be reflected in the same amount of wavelength variation.

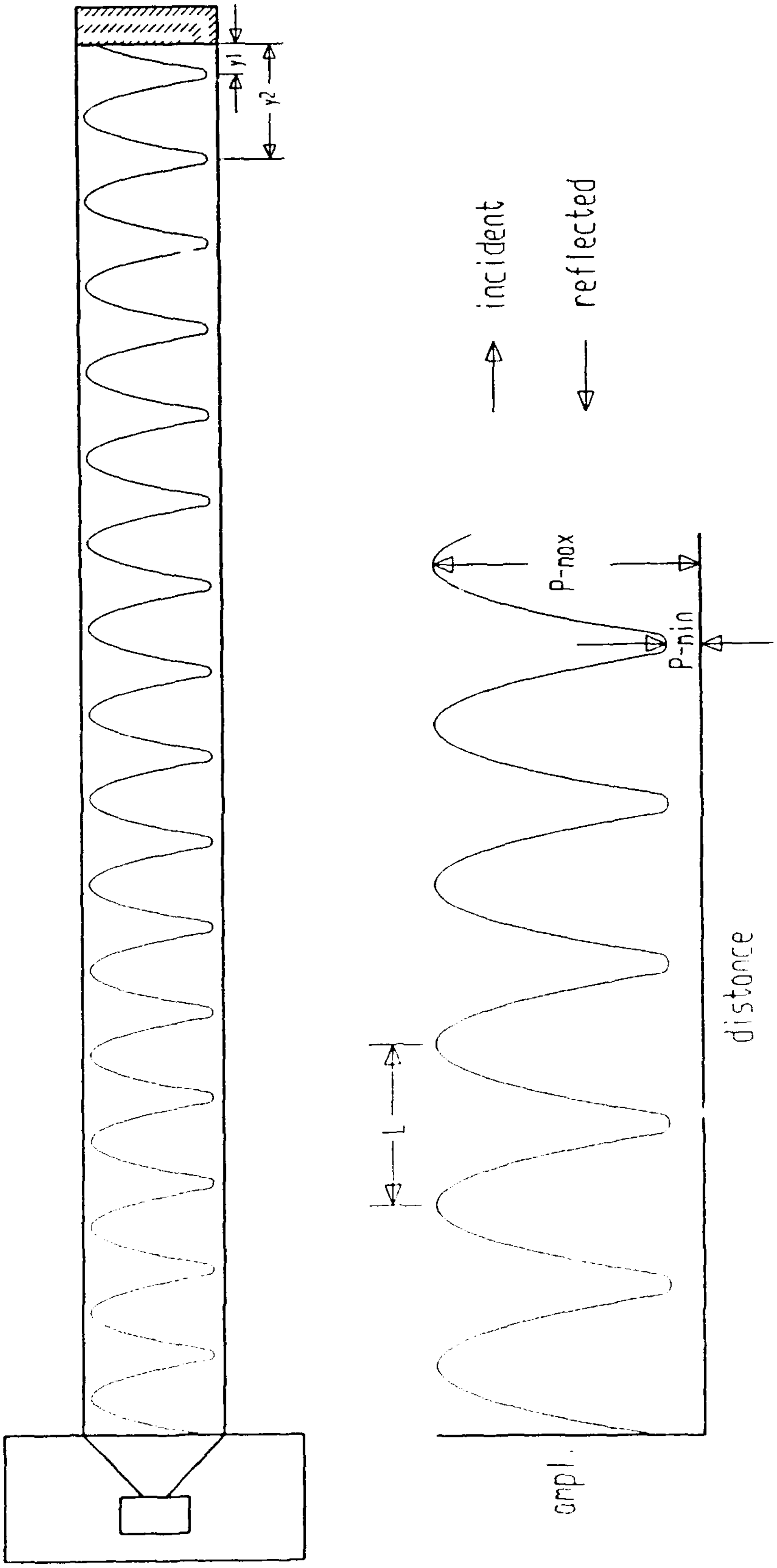

Fig. A–1. Variation of sound amplitude in the tube due to interference between the incident and reflected waves.

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Negative Poisson's ratio (NPR) materials have been predicted to have unusual acoustic properties. To measure this effect, polyurethane foam was chosen to serve as a model system. Negative Poisson's ratios were produced from open cell, reticulated polyurethane foams by heat setting the foam which was compressed in three dimensions to a volume smaller by the factor 3.7 than the original volume. Acoustic tests comparing the reflection properties of the unconverted, the NPR uncovered, and the NPR foam with an attached cover, and one with an unattached covering were made on foams with pore sizes ranging from 10 to 100 pores per linear inch. Uncovered NPR foams reflected less sound at all frequencies than the uncovered unconverted foam. Smaller pore size NPR foams absorbed sound more efficiently at frequencies above 630 than did those with larger pores, and those with covers were better sound absorbers in the frequency range 250 to 1000 Hz than the uncovered NPR foams. Unidirectional compression to 1/4 the original thickness reduced the Poisson's ratio to zero and caused the foam to absorb nearly as well as did creation of the negative Poisson's ratio.

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